ACCELERATION OF INTENSE FLAT BEAMS IN PERIODIC LATTICES

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Abstract

Recently a scheme for creation of flat ion beams from linacs has been proposed to increase the efficiency of multi-turn-injection. The proof of principle experiment shall be performed at GSI in Summer 2014. Since the scheme requires charge stripping, it may be necessary to perform the round-to-flat transformation prior to acceleration to the final energy of the linac. This requires preservation of the beam flatness during acceleration along the drift tube linac. This contribution is on simulations of acceleration of flat beams subject to considerable space charge tune depression. It is shown that the flatness can be preserved if the transverse tunes are properly chosen and if mismatch along inter-tank sections is minimized along the DTL.

MOTIVATION

GSI is currently constructing the Facility for Antiproton and Ion Research (FAIR). The existing UNILAC [1] will serve as injector of primary beams. As reference ion serves $^{238}U^{28+}$ to be delivered by the UNILAC with pulsed electrical current of 15 mA at the injection into the subsequent synchrotron SIS18. The latter applies the horizontal multi-turn injection scheme. As a consequence the injection acceptances in the transverse planes differ, i.e. they are, in terms of normalized total emittances, about 1.0 mm mrad in the horizontal plane and about 3.0 mm mrad in the vertical plane. Although the injection acceptance is flat, the beams delivered from linacs are usually round. Round-to-flat transformation of linac ion beams should be an appropriate tool to significantly increase injection efficiency into flat-injection-acceptance accelerators.

FLAT BEAM GENERATION

A round-to-flat adapter for linacs has been proposed in [2, 3] and was recently tested with beam at GSI [4]. The adapter comprises a charge state stripping foil installed in the center of a solenoid followed by a skew quadrupole triplet. Stripping inside the solenoid changes the transverse eigen-emittances [5] of the beam and creates inter-plane correlations. Skew quadruplets remove these correlations while leaving the eigen-emittances unchanged. The adapter has the very convenient feature, that it provides at its exit beams with constant Twiss parameters β and α in all planes, while the transverse emittance ratio ϵ_y/ϵ_x can be varied just through the solenoid field strength [6].

As the reference ion for FAIR is $^{238}U^{28+}$, the adapter must be installed where the charge state $^{238}U^{28+}$ is created by gaseous stripping of a $^{238}U^{4+}$ beam at 1.4 MeV/u. This gaseous stripper is installed prior to GSI's Alvarez type DTL. Accordingly, stripping prior to the DTL imposes the challange to accelerate an intense beam of unequal transverse emittances without significant degradation of the beam quality, i.e. transmission, emittance ratio, and absolute emittance values.

ACCELERATION ALONG SYMMETRICALLY FOCUSING DTL

The Alvarez type DTL of GSI's UNILAC (Fig. 1) accelerates all ions from protons to uranium from 1.4 MeV/u to 11.4 MeV/u. It comprises five rf-tanks. Along each tank

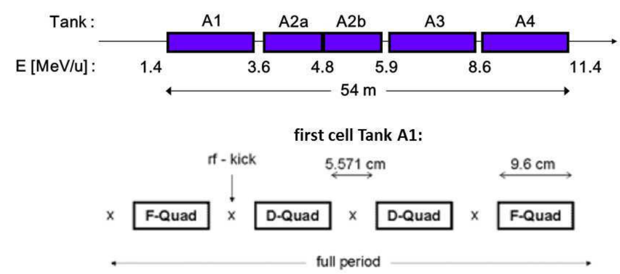

Figure 1: Scheme of the DTL (top) and its first cell (bottom).

transverse symmetric FFDD-focusing is applied, i.e. the two undepressed tunes are equal in the horizontal and the vertical plane. Emittance growth mitigation along the first tank by proper 3d-envelope matching including space charge has been demonstrated experimentally [7]. However, the inter-tank sections just apply DFD-focusing without any longitudinal focusing. Accordingly, each of the four inter-tank sections is a seed of emittance growth from envelope mismatch. The design of the DTL is from the 1970ies and space charge forces were not an issue at that time. Previous works [7] have shown that beams being space charge equivalent to 15 mA of $^{238}U^{28+}$ are accelerated with minimized emittance growth if the transverse zero current phase advance $\sigma_{\perp 0}$ of 70° is applied. The undepressed longitudinal phase advance of 44° is given by the synchronous phase of -30° along the first three tanks and -25° along the last two tanks. In the following we assume 15 mA of beam current and as initial normalized longitudinal rms-emittances in front of the DTL 0.052 deg mrad, referring to the rf-frequency of 108 MHz and to relative momentum spread.

Firstly, the sensitivity of the periodic solution w.r.t. the amount of flatness (transverse emittance ratio) was investigated. For emittance ratios ranging from 1 to 8 the periodic solutions have been calculated including space charge. They are listed in Tab.1. The dependence of the periodic solution from the amount of flatness is quite weak implying that re-matching of the envelope Twiss parameters β and α in all three planes for each transverse emittance ratio can be skipped in practice. This feature together with

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Table 1: Initial Emittance Ratios, Corresonding Tunes, and Periodic Solutions with Space Charge. The α-parameters in each plane is practically equal to zero. The longitudinal beta function β_l is always equal to 3.0 m and the vertical beta function β_y is always equal to 0.4 m. The product of the two transverse emittances is kept constant.

ϵ_y/ϵ_x	σ_x [deg]	σ_y [deg]	σ_l [deg]	β_x [m]
1	50	50	28	1.3
2	46	53	28	1.3
3	44	55	28	1.4
5	42	57	28	1.5
8	40	59	28	1.6

the property of constant Twiss parameters provided at the exit of the round-to-flat adapter [6] facilitates significantly the operation of a flat beam DTL: the desired transverse emittance ratio is set with the solenoid, no further beam adoption is required. However, this contribution is restricted to the transverse normalized rms-emittance ratio ϵ_y/ϵ_x of 0.44/0.12 being close to the acceptance ratio of the synchrotron into which the linac beam finally has to be injected. The corresponding stability chart at the entrance to the DTL is shown in Fig. 2. Beam acceleration with space charge

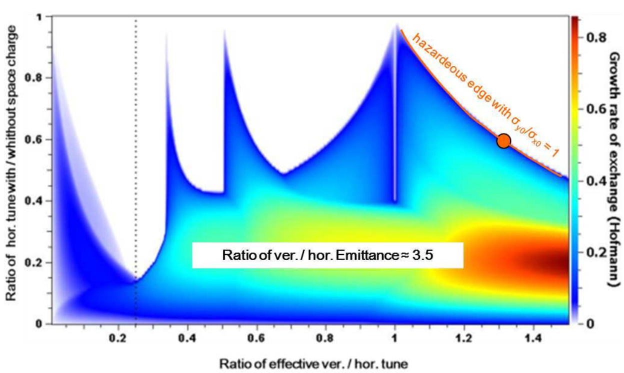

Figure 2: Stability chart for the ver/hor emittance ratio of 3.5 at the entrance to the existing Alvarez type DTL of the GSI UNILAC.

is simulated using DYNAMION [8]. As initial distribution serves a result from front-to-end simulations starting from the source. Figure 3 displays the evolution of the transverse emittances along the DTL. Along the first tank the smaller (hor) emittances rapidly increases while the larger (ver) emittance decreases. Massive loss of flatness is observed. This is in agreement with the prediction of the stability chart as the working point is just on the right edge of the resonance, i.e. related to equal undepressed transverse tunes. The convergence of the two emittances is stopped after passing the first inter-tank section. It imposes mismatch and stops the equipartitioning occurring along the first tank, where the envelope is well matched. After the inter-tank section the horizontal emittance remains almost constant but the vertical one increases significantly.

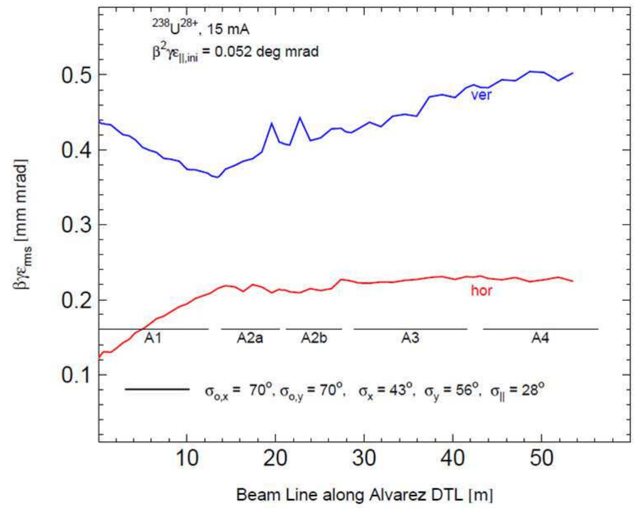

Figure 3: Normalized horizontal and vertical rms-emittances along the beam line. The assumed DTL is the existing GSI Alvarez type DTL.

The influence from inter-tank mismatch was investigated by prolonging artificially the first tank such that acceleration to the final energy is assumed to happen without any inter-tank section, i.e. without periodic lattice interruption. The emittance evolution for this case is shown in Fig. 4. The

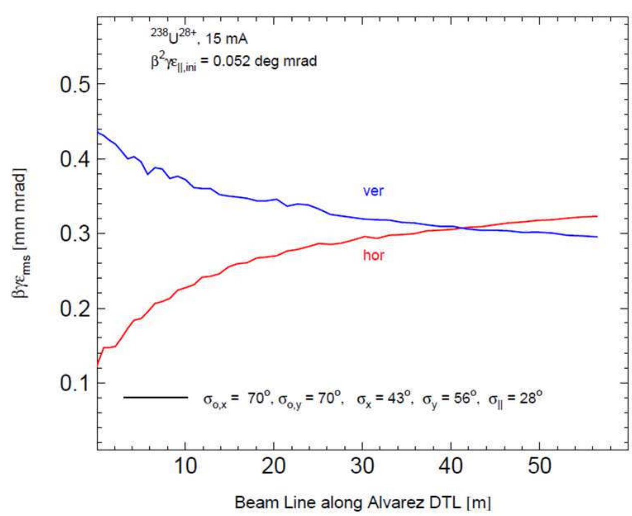

Figure 4: Normalized horizontal and vertical rms-emittances along the beam line. The assumed DTL is the artificially prolonged existing first tank A1, i.e. without inter-tank sections.

equipartitioning is ongoing in this case. It is just mitigated by the suppression of space charge from acceleration.

ACCELERATION ALONG ASYMMETRICALLY FOCUSING DTL

De-flattening is mainly due to equipartitioning driven by space charge and improper choice of the working point in the stability diagram (Fig. 2). The working point can be shifted by using asymmetric transverse focusing, i.e. by applying stronger focusing in one transverse plane w.r.t. the other one. As DTLs usually apply groups of quadrupoles being designed identically, the asymmetry could be realized by just driving the vertical focusing quadrupoles stronger than the horizontally focusing ones for instance. This is the way it has been done in the simulations and the according shifts of the working point are indicated by arrows in Fig. 5. Increase of vertical focusing moves the working point to the

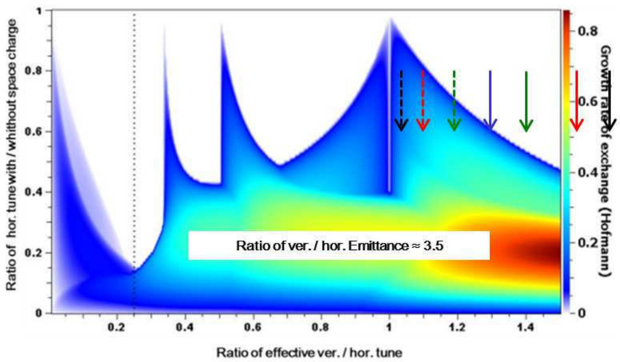

Figure 5: Stability chart and working points for the ver/hor emittance ratio of 3.5 at the entrance to the existing Alvarez type DTL of the GSI UNILAC assuming different focusing strength in the transverse planes.

right, i.e. away from the hazardous edge of the resonance. Seven different transverse focusing strength ratios σ_{y0}/σ_{x0} have been used in the simulations. The resulting behaviours of transverse emittances along the DTL are summarized by Fig. 6. Acceleration causes de-flattening if the zero current phase advance in the horizontal plane is equal or larger than the vertical one. In turn, the flatness is practically preserved if the vertical zero current phase advance is larger w.r.t. horizontal one. For preservation of flatness the hor/ver tune ratio has to be larger than 1.05. Strongest intergral de-flattening occurs for symmetric transverse focusing, i.e. $\sigma_{x0} = \sigma_{y0}$, being the case for a regular periodic DTL. If the tunes differ de-flattening is locally strongest at the beginning of the DTL. The amount of de-flattening scales with the tune ratio σ_{x0}/σ_{y0} as suggested by the stability chart of Fig. 5. If equipartitioning is very strong, as for $\sigma_{x0}/\sigma_{y0} = 1.05$ for instance, the transverse emittances are changed so significantly, that the stability chart itself changes its shape and equipartitioning comes to an end or is even reversed (green dotted curve in Fig. 6).

CONCLUSION

Beams being subject to significant space charge forces and having different transverse emittances, can be accelerated with good preservation of the initial transverse emittance ratio. But to achieve that preservation, the lattice must avoid or at least sufficiently minimize any interruption of the periodicity. Special emphasis must be put on proper beam dynamics design of the inter-tank sections. Good envelope matching to the periodic lattice in all three planes including

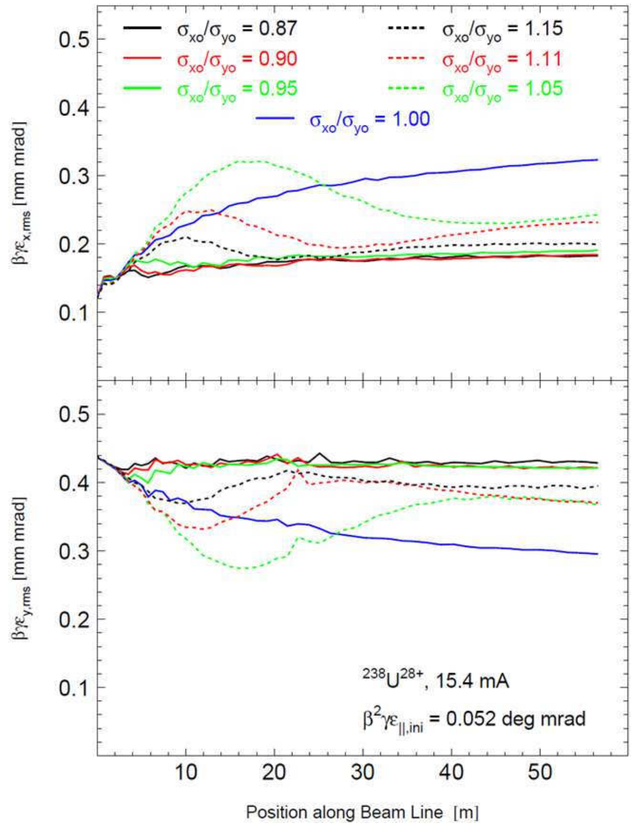

Figure 6: Normalized horizontal and vertical rms-emittances along the beam line. The assumed DTL is the artificially prolonged existing first tank A1. Additionally, the horizontal and vertical tunes are different by powering horizontally and vertically focusing quadrupoles differently.

space charge is mandatory. Additionally, the lattice must exert stronger focusing in the plane with the larger emittance w.r.t. the other plane.

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